

## RESEARCH AND ANALYSIS

# Global material flow analysis of glass

## From raw materials to end of life

Coenraad D. Westbroek | Jennifer Bitting | Matteo Craglia  | José M. C. Azevedo  | Jonathan M. Cullen 

Department of Engineering, University of Cambridge, Cambridge, UK

**Correspondence**

Jonathan M. Cullen, Department of Engineering, University of Cambridge, Trumpington Street, Cambridge, CB2 1PZ, UK.  
Email: [jmc99@cam.ac.uk](mailto:jmc99@cam.ac.uk)

Editor Managing Review: Eric Masanet

**Funding information**

MC was funded under Engineering and Physical Sciences Research Council (EPSRC), UK grant numbers EP/M506485/1 and EP/M508007/1. JMCA was supported by EPSRC grant number EP/S019111/1.

**Abstract**

Global glass production grew to 150 million tonnes (Mt) in 2014, equating to approximately 21 kg per person. Producing this glass is energy intensive and contributes annual CO<sub>2</sub> emissions of some 86Mt. An accurate map of the global glass supply chain is needed to help identify emissions mitigation options from across the supply chain, including process energy efficiency and material efficiency options. This map does not yet exist, so we address this knowledge gap by tracing the production chain from raw materials to end of life and producing a global Sankey diagram of container and flat glass making for 2014. To understand future demand for flat glass we also model the stocks of glass in vehicles and buildings. The analysis shows the relative scale of glass flows and stocks worldwide and provides a baseline for future study of the emission mitigation potential of energy and material efficiency of manufacturing with glass.

**KEYWORDS**

dynamic modeling, emission reduction, energy efficiency, glass, materials efficiency, material flow analysis (MFA)

## 1 | INTRODUCTION

The production of glass is energy intensive and results in significant global CO<sub>2</sub> emissions, contributing around 86 Mt<sup>1</sup> of CO<sub>2</sub> or some 0.3% of worldwide emissions (IEA, 2020). However, while other more intensive and impactful engineered materials have been mapped globally in detail—for example, steel (Cullen et al., 2012; Pauliuk et al., 2013b), aluminum (Cullen & Allwood, 2013), pulp and paper (Van Ewijk et al., 2018), cement (Cao et al., 2017), petrochemicals (Levi & Cullen, 2018)—less has been written about the global glass production system. In fact, to obtain credible estimates of the global energy use and emissions in the glass industry, one must return to the International Energy Agency report (IEA, 2007). Furthermore, a map of the flows of glass, through the global production system, does not exist, despite being critical for understanding the drivers of energy use and emissions, exploring mitigation options across the entire supply chain, and proposing solutions for reaching climate change targets.

Global demand for glass products in 2014 was approximately 150 million tonnes (Mt) (Butler & Hooper, 2019), made up of 48% hollow or container glass, 42% flat glass (for windows in construction and vehicles), 5% tableware, and 6% other products (such as glass fibers) (Harder, 2018). Demand for glass is expected to continue to grow (Lucintel, 2016). Therefore, addressing energy use and emissions in the glass industry is important.

Glass is in theory indefinitely recyclable, and therefore, could be a key material in a future circular economy where waste no longer exists, material loops are closed, and products are recycled indefinitely (Cullen, 2017). The use of cullet—the industry name for recycled glass—avoids the process emissions released during production of virgin glass. In addition, each 10% increase of cullet input to the melting process decreases the furnace

<sup>1</sup> Figure obtained by multiplying the global production of glass reported by Butler & Hooper (2019) with the CO<sub>2</sub> intensity of glass making reported by Schmitz et al. (2010)

This is an open access article under the terms of the [Creative Commons Attribution](https://creativecommons.org/licenses/by/4.0/) License, which permits use, distribution and reproduction in any medium, provided the original work is properly cited.

© 2021 The Authors. *Journal of Industrial Ecology* published by Wiley Periodicals LLC on behalf of Yale University

energy consumption by about 2.5–3.0%, due to the lower melting temperature requirement for cullet compared to virgin feedstock (Scalet et al., 2013). Hence, replacing all virgin feedstock with cullet results in 25–30% furnace energy saving. When examining the emissions released over the entire cradle-to-cradle life cycle, including collection, sorting, and cleaning, recycling glass still makes sense. The Glass Packaging Institute (2014) states that producing container glass from cullet, instead of virgin feedstock, results in reduced primary energy demand (PED) and savings of up to 37% in life cycle CO<sub>2</sub> emissions.

The case for recycling is thus strong, due to savings in emissions in the melting furnace and over the life cycle, however global recycling rates remain low. Harder (2018) estimates recycling volumes to be 27Mt per year, representing only 21% of the total glass produced. For container glass, the global recycling rate is approximately 32%, despite reaching 70% in some countries. The recycled content in flat glass making is as low as 11%, limited by the need to maintain precise chemical composition in the soda–lime–silica glass (Harder, 2018). Contrary to flat glass, container glass can be reused, but the reuse rate is only 4% in the European Union and lower in the rest of the world (Butler & Hooper, 2019).

Combining the significant growth in demand for glass and the potential of CO<sub>2</sub> emission savings from recycling glass, compels the investigation of other mitigation options. However, to be able to explore wider mitigation strategies, for example, material efficiency options, requires a clear understanding of the material flows and stock dynamics for the global glass supply chain.

Glass making is energy intensive due to the high temperatures (about 1500°C) required for melting the raw materials into glass (Butler & Hooper, 2011). Levine et al. (2003) estimate that expenditure on energy accounts for roughly 15% of the total glass production costs. The energy intensity of glass production is estimated to be around 7–8 GJ/t (IEA, 2007). This is less than other energy intensive industries such as steel, 20–30 GJ/t, and aluminum, 90–100 GJ/t, but more than cement, 3–6 GJ/t (Schmitz et al., 2010).

There are two main sources of CO<sub>2</sub> emissions in glass making (Scalet et al., 2013). Energy emissions are released to provide heat for melting the glass, typical from burning natural gas in the melting furnace. Process emissions are released when the limestone and soda ash inputs to glass making decomposes upon heating. In the European Union, combustion emissions account for roughly 62% of the CO<sub>2</sub> emissions burden, other energy uses account for 21% and process emissions for the remaining 16% (Schmitz et al., 2010).

Efforts to reduce emissions from glass production focus on energy emissions and on process emissions. Energy-derived emissions from the melting process can be reduced through energy efficiency improvements, substitution of fossil fuels by low-carbon fuels, utilizing waste heat, and incorporating renewable power supplies (Scalet et al., 2013). Process CO<sub>2</sub> can be reduced using carbon capture and storage (CCS) and substituting virgin materials with cullet (Scalet et al., 2013). However, these measures have their limitations. CCS is still an immature technology and the deployment rate of renewable power supplies is slow. The supply of recycled glass remains limited, due to a lack of global legislation on glass recycling and because stock dynamics limit the availability of discarded flat glass. Even under the most optimistic scenario where glass is made from 100% recycled material, emission reductions are still limited to less than 50%.

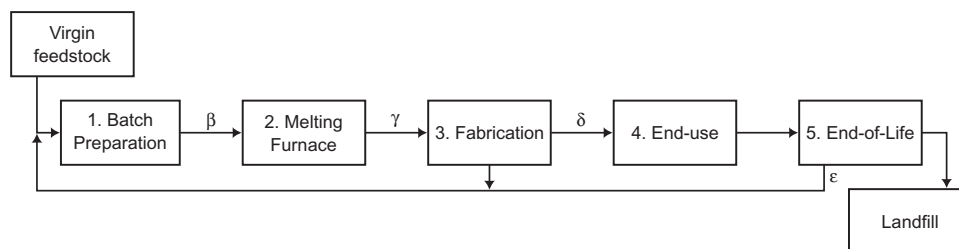
There is scope to reduce energy use and CO<sub>2</sub> emissions by electrifying heat generation in glass making. However, fully electric furnaces are only used to make specialty glass products (Worrell et al., 2008). Springer and Hasanbeigi (2017) did not consider electrification in their study of new technologies to reduce energy and CO<sub>2</sub> emissions in glass making because the emission savings depend on the electricity grid mix. Furthermore, electricity is generally more expensive than fuels, so it is not economically advantageous to switch from fuels to electricity (Brinckerhoff, 2015).

Given these challenges, the opportunity to reduce emissions through material efficiency and demand reduction should be explored. Examples of material efficiency strategies for glass include using less materials by design, creating longer-life products and using materials more intensely. Existing research into emissions abatement in glass production often overlooks the potential of material efficiency. Brinckerhoff (2015) proposed a roadmap to decarbonize the UK glass industry by 2050 but did not consider material efficiency and Schmitz et al. (2010) studied the emissions from glass making in the European Union but did not investigate the potential of material efficiency to improve resource efficiency.

An accurate map of the global glass supply chain is necessary to identify where material efficiency options might have the greatest impact. This map would provide a key link between material efficiency actions and the resulting upstream emissions abatement. Previous studies which map the flow of glass focus on regional areas and typically exclude flat glass sector. For example, Sandgren (1996) conducted a material flow analysis for the US packaging industry, focusing on glass bottles. While, British Glass (2008), which “represents the interests of primary glass manufacturers and the glass supply chain,” conducted a mass balance study in 2008 of the UK glass industry. Tsai and Krogmann (2013) performed a material flow and energy analysis of glass containers discarded in New Jersey, USA. Wiedenhofer et al. (2019) modeled global material flows and stocks of container and flat glass but did not distinguish between the different uses of glass nor identified opportunities to reduce CO<sub>2</sub> emissions in the supply chain of glass.

Given there is currently no global map of the glass production system, this paper seeks to:

- Create a detailed map of glass flows, showing the flows from raw materials to end of life, considering melting losses, yield of fabrication, end-uses, and recycling rates. The analysis focuses on container and flat glass products which make up around 90% of all glass production (European Commission, 2012).
- Create a dynamic stock model for two flat glass end-use sectors, that is, buildings and automotive applications. Measuring the in-use stock of glass products provides a better picture of service delivered by glass, than the production of glass, which is especially true for products with relatively long lifetimes. This model is also essential to quantify the future availability of end-of-life scrap material and understand recycling potentials.



**FIGURE 1** Glass supply chain block diagram

**TABLE 1** Summary of data sources and assumptions used to map the global flows of glass in 2014

Processes	Description, data sources and assumptions
Batch preparation	<i>Soda ash, limestone, silica, and cullet are mixed together.</i> 90% of all glass is made from soda–lime–silicate (Robertson, 2005), which consists of 15% soda, 10% lime, and 75% silica (Shelby, 2005). According to Butler and Hooper (2011), the global container glass recycling rate ( $\epsilon$ ) is approximately 30–35% and it was assumed that all the container glass collected at the end of life is used to make new containers (Butler and Hooper (2019) mention that end-of-life cullet is not significantly used in flat glass production).
Melting furnace	<i>The batch mix is heated to 1500°C to melt the raw materials and produce glass.</i> The yield of melting ( $\beta$ ) was estimated at approximately 85% (calculation described in Supporting Information S1). This value was used for flat and container glass melting.
Fabrication	<i>Molten glass is transformed into either flat or container glass.</i> Globally, 71 Mt of flat glass and 79 Mt of container glass were produced in 2014. The flat glass flows were estimated using data from Glass for Europe (2018), United Nations (2019), and other sources. The production of container glass was estimated using data from Butler and Hooper (2019) and other data at national or continental levels. The sources and assumptions used to estimate these flows are described in Supporting Information S1. The yield of fabrication ( $\gamma$ ) was 85% for flat glass and 90% for container glass, these values were reported by British Glass (2008).
End-use	<i>Fabricated products are allocated to end-uses in the container and flat glass industry (<math>\delta</math>).</i> Most of flat glass is used in construction and automotive sectors and Pilkington (2010) reported that globally in 2009, 83% was used in construction, 6% was used in the automotive sector, and the remaining 11% were used in other sectors. No global end-use data were found for container glass, but sector splits were reported by European Commission (2008) for the European Union (75% beverages, 20% food, and 5% other) and by Glass Packaging Institute (2014) for the United States (81% beverages, 19% food). Since the two distributions are similar, and around one third of all the glass is produced in the European Union (European Commission, 2012), the European Union fractions were used to produce the global map.
End-of-life	The flows of flat glass at the end of life were provided by Butler and Hooper (2019). It was assumed that container glass has a lifetime below 1 year and is either recycled, disposed to landfill, or incinerated (according to $\epsilon$ ).

## 2 | CONSTRUCTING A MAP OF GLOBAL GLASS FLOWS

This section explains the methods used to map the global flows of glass and estimate the total quantity of glass that is currently in use. First, the global flows of glass, from raw materials to final product, are constructed for a single year using a static material flow analysis. Next, the stocks of existing glass and future flows of glass are estimated using a dynamic material flow analysis.

### 2.1 | Static material flow analysis

The glass supply chain consists of five steps, shown in Figure 1. There are two major global flows of glass, the production of flat and container glass. The map was constructed from estimates of these two flows, which are between blocks 3 and 4 of Figure 1. The remaining flows are a function of container and flat glass production, and Table 1 outlines the main data sources and assumptions used to construct the diagram. The base year for the analysis is 2014, due to availability of data for that year.

The flows for batch preparation were obtained using the batch-to-melt yield ( $\beta$ ). This parameter accounts for the material “losses” that occur during melting. These losses are mostly due to the formation of CO<sub>2</sub> during the chemical reactions that transform raw materials into glass. After melting, the glass is either transformed into flat sheets, by the float glass method, or formed into containers. These fabrication processes create a small fraction of material which fails to meet the product requirements, and hence is remelted within the factory. This was modeled with the yield of fabrication ( $\gamma$ ). As reported in Table 1, data was found on the mass of produced flat and container glass and these two flows were distributed according to the sector split ( $\delta$ ), which represents how the mass of glass is distributed to specific applications. After use, glass is either disposed to landfill or incinerators or recycled; data were only found for container glass recycling which was modeled using the container glass recycling rate ( $\epsilon$ ).

**TABLE 2** Flows of glass leaving and entering the building stock. The data reported by Butler and Hooper (2011) was multiplied by 83% which is the proportion of flat glass supplied to buildings according to Pilkington (2010)

Year	Out [Mt]	In [Mt]	Source
2006	2.7	36.5	Butler and Hooper (2011)
2014	12.4	58.8	Figure 2

Even though anecdotal evidence was found on the use of end-of-life cullet in flat glass making (de Lummen & Schreuder, 2013; Saint-Gobain, 2009), our map assumes that no end-of-life cullet is used to make flat glass because no global data on this was found. Flat glass cullet can also be used as an input to container glass making (Scalet et al., 2013), but no data on this was found in the literature so this flow was also not represented in the map.

Material flow analysis results are inherently uncertain due to varying quality and availability of data (Laner et al., 2014). This uncertainty can be better understood by conducting a sensitivity analysis to assess the variation in the results from changing selected model parameters. This is achieved by analyzing how the main flows of glass respond to a 1% increase in each of the four key parameters ( $\beta$ ,  $\gamma$ ,  $\epsilon$ ,  $\delta$ ). This assessment can identify where future work can contribute to reducing the uncertainty of the results.

A static material flow analysis determines the magnitude of the flows of glass that occur in a single year. This links the annual consumption of raw materials to the production of final products. However, a stock model is required to estimate the potential for recycling end-of-life scrap glass in the future. A stock model of glass would also facilitate the prediction of future demand for glass. The following paragraphs describe how the global stocks of glass were estimated.

## 2.2 | Dynamic material flow analysis of flat glass

Forecasting the future global demand for glass and the availability of scrap glass from previous years requires a stock model. A stock model, created using dynamic material flow analysis, accounts for the lifetimes of glass products and changes in the stock levels. Container glass products are assumed to have a lifetime of less than a year, so a stock model for these products is not necessary. Flat glass products are mostly used in vehicles and buildings, hence have much longer lifetimes.

The dynamic material flow analysis proposed in this paper builds on the work of Pauliuk et al. (2013a), who estimated in-use stocks of steel. Many of the end-use applications for steel are similar to the end-use applications for glass, as both materials are commonly used in the construction and transportation sectors. Therefore, lifetime estimates for steel used in buildings and vehicles were used to estimate lifetimes for glass products. Glass stocks were calculated by estimating how much glass is used in vehicle manufacturing and the construction sector.

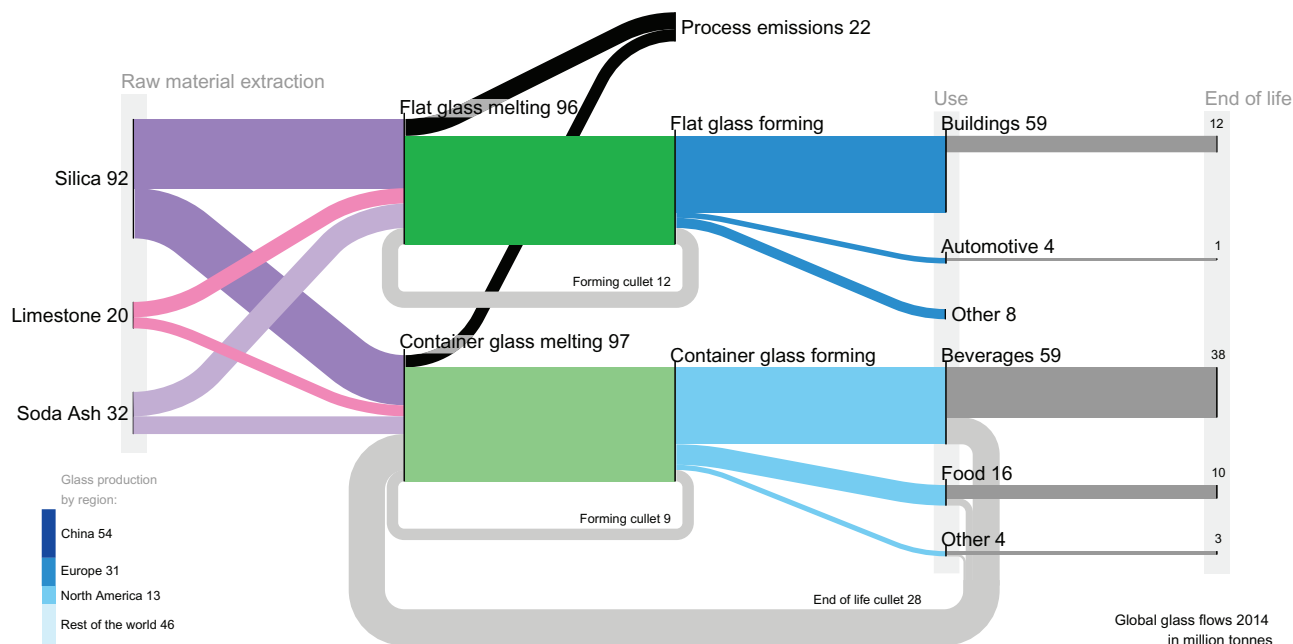
### 2.2.1 | Glass in the global passenger vehicle fleet

The stocks and flows of glass over time were estimated using the approach proposed by Müller (2006) which considers the size of the population, the number of service units and their lifetime, and the material associated with these service units. The size of the global population and the number of vehicles per person have been estimated by Modaresi et al. (2014) and were used as input parameters to the stock model proposed by Müller (2006). A vehicle lifetime distribution with a mean of 13 years (Cooper et al., 2014) and a standard deviation of 30% of the mean was considered. This stock model was implemented in Python by Pauliuk and Mutel (2014) and this implementation was used in this work to calculate the stock of flat glass in cars and the inflows and outflows of materials to stock between 1950 and 2050.

The mass of glass in vehicles is estimated with data on the glass content of new vehicles sold between 1995 and 2014 in the United States, sourced from Dai et al. (2016). The average value of 44 kg of glass in every vehicle was used since the amount of glass varied by less than 2% between 1995 and 2014. The stock model runs from 1950 until 2050 but no glass content data was found for other years.

### 2.2.2 | Glass in the global building stock

Global steel stock data for buildings is sourced from Pauliuk et al. (2013a). This is converted into global glass stocks using the data points for flows into and out of stocks described in Table 2. The amount of glass reported in Table 2 was divided by the flows of steel into the building stock reported by Pauliuk et al. (2013a) to obtain the ratio between glass and steel. This ratio was used to estimate the flows of glass into the building stock. It was assumed that this ratio was constant over time.



**FIGURE 2** Global flows of glass in 2014, from raw materials to end of life (the width of the lines is proportional to the mass of flows). This diagram was designed with floWeaver (Lupton & Allwood, 2017)

The steel stock model proposed by Pauliuk et al. (2013a) predicts future demand for steel based on the assumption that steel stocks saturate. This assumption is supported by evidence in developed countries which was compiled by Pauliuk et al. (2013b). For construction, a stock saturation level of 10 t per person and a lifetime of 75 was used to predict steel stocks. Multiplying the global steel stock data for buildings (Pauliuk et al., 2013a) by the glass to steel ratio, allows the calculation of glass stocks. In the year 2014, these were equal to 1620 Mt of glass products in buildings worldwide.

The full data and code used to model stocks and produce the figures in the article are available online (Azevedo, 2020).

### 3 | RESULTS

#### 3.1 | Global static material flow analysis of glass

Figure 2 shows the map of global glass for 2014, which traces the flow of glass from raw materials to end of life. The width of each flow is proportional to its mass and values are reported in million tonnes (Mt). The glass life cycle starts on the left-hand side of the diagram with the batch preparation of 144 Mt of virgin raw materials and 28 Mt of cullet (recycled glass). The batch melts in the furnace, resulting in intermediate flat glass products (96 Mt) and container products (97 Mt), and the release of process emissions (22 Mt), due to the decomposition of virgin feedstock.

The intermediate products are reworked, cut-off, and checked for deficiencies, which results in fabricated flat products (71 Mt) and container products (79 Mt), along with internally recycled cullet. The fabricated (final) products are in the form of flat glass, with 83% used in buildings, and container glass, with 75% used for beverages. End-of-life container glass is either recycled or sent to landfill. The availability of end-of-life flat glass cullet is limited by stock dynamics. The lifetime of flat glass used in the building and automotive sector was assumed to be 75 years and 13 years, respectively. The lifetime of container glass is less than 1 year, except for the fraction of containers that are reused. Hence, there is little stock accumulation of container glass and end-of-life cullet becomes a new product in the same year.

#### 3.2 | Sensitivity analysis

The sensitivity analysis, shown in Table 3, displays the percentage change in each of the mass flows due to a 1% change in each of the four main process parameters. Changing the yield of fabrication ( $\gamma$ ) results in the biggest changes in material flows. Followed by altering the sector split ( $\delta$ ), the batch-to-melt yield ( $\beta$ ), and the container glass recycling rate ( $\epsilon$ ). Increasing the yield of fabrication parameter ( $\gamma$ ) substantially reduces the amount of internally recycled material, mostly in the container glass industry. This means less material is cycled back to the furnace, which reduces the

**TABLE 3** Relative variation of the mass flows in Figure 2 due to a variation of: Batch-to-melt yield ( $\beta$ ); yield of fabrication ( $\gamma$ ); container glass recycling rate ( $\varepsilon$ ); and sector split ( $\delta$ ). Only flows that varied by more than 2% are shown

Source	Target	$\beta$ (+1%)	$\gamma$ (+1%)	$\delta^a$	$\varepsilon$ (+1%)
Container glass melting	Process emissions	92%	—	—	98%
Flat glass melting	Process emissions	92%	—	—	—
Container glass forming	Container glass melting	—	89%	—	—
Flat glass forming	Flat glass melting	—	92%	—	—
Container glass forming	Use of container glass (other)	—	—	90%	—
Flat glass forming	Use of flat glass (automotive)	—	—	92%	—
Flat glass forming	Use of flat glass (other)	—	—	95%	—
Use of container glass (beverages)	Container glass melting	—	—	101%	103%
Use of container glass (food)	Container glass melting	—	—	98%	103%
Use of container glass (other)	Container glass melting	—	—	90%	103%
Use of container glass (other)	Disposal	—	—	90%	98%

<sup>a</sup> +1% for buildings and beverages and −0.5% for the rest; — means that the flow did not change.

energy requirements for each unit of glass output. Improving the batch-to-melt yield ( $\beta$ ) decreases process emissions. Increasing the recycling rate ( $\varepsilon$ ) of container glass reduces the need for virgin feedstock in the container batch.

### 3.3 | Global dynamic material flow analysis of glass

The stock of flat glass used in buildings outweighs that used in vehicles (comparison of Figure 3b with Figure 3d), due to the longer lifetimes for buildings. Both stocks of glass will continue to grow for the foreseeable future as the inflows of new glass into stocks are larger than the outflows (Figure 3a,c).

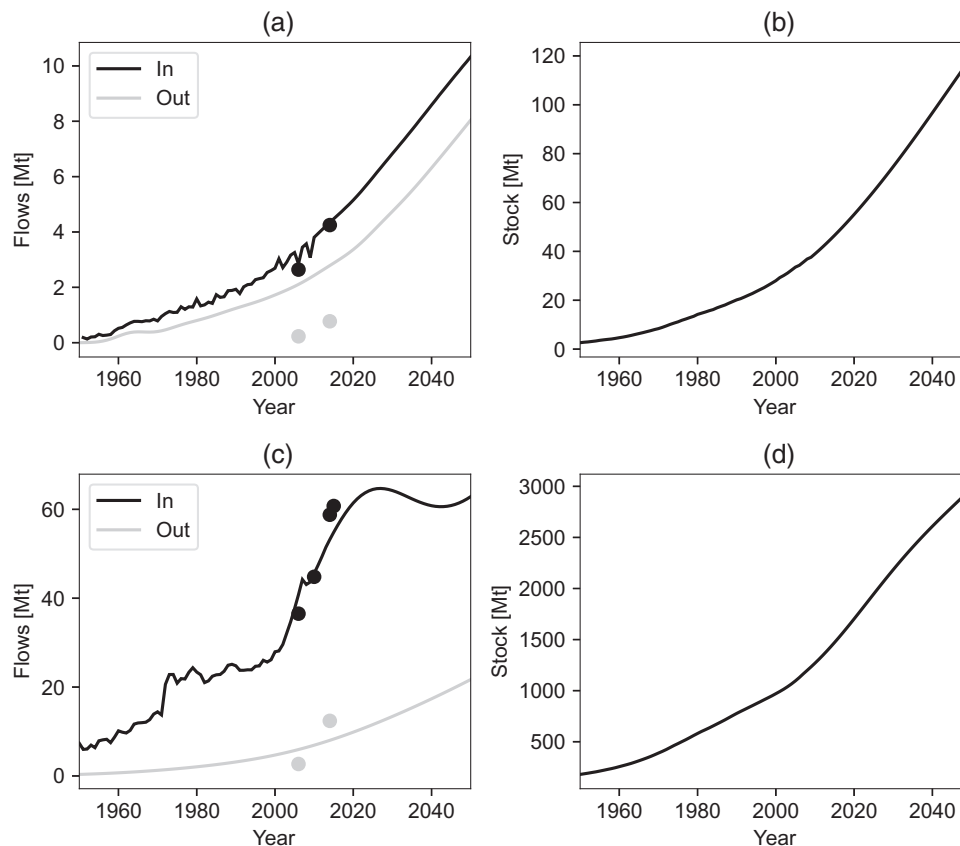
Figure 3a shows measured flows of glass to the stock of vehicles, for 2 years. The values of inflows match well with the modeled curves. However, the modeled value of flows leaving the stocks is larger than the two measured flows. This difference can be due to the measured values of outflows not covering the whole world. There might be more uncertainty on the measurement of flows leaving the stocks. In the case of use of glass in vehicles, the circles represented in Figure 3a were not used to calibrate the model, hence are two independent representations of the flows of glass. Figure 3c shows that the measured flows of glass into the building stock are close to the model. The data points of 2006 and 2014 were used to calculate the ratio of glass to steel in buildings. However, this figure shows additional points that follow the same trend of the model (but were not used to calibrate it).

## 4 | DISCUSSION

The map of the global glass supply chain (Figure 2) and the future stock estimates and glass flows (Figure 3) reveal opportunities for resource efficiency improvements within the glass supply chain. This section discusses the implication of these results, starting with the static analysis, followed by the estimates of glass stocks, and ending with a discussion on material efficiency options.

### 4.1 | The global glass supply chain

The global glass supply chain comprises four major product types: building and automotive flat glass and food and beverage glass produced by two manufacturing processes (float glass manufacturing and glass forming) with two materials with similar chemical compositions but different requirements. The Sankey diagram in Figure 1 shows the flows of these two materials. Contrary to container glass, flat glass is not commonly recycled at the end of life due to more stringent requirements of cullet purity. Little global data was found to quantify the amount of cullet feed to flat glass production. However, using recycled content in flat glass is technically feasible, with Saint-Gobain Glass UK reporting “30% recycled cullet in the manufacture of its float glass” (Saint-Gobain, 2009). In practice, most end-of-life flat glass from buildings is downcycled into construction aggregates, according to Butler and Hooper (2019).



**FIGURE 3** Global dynamic material flow analysis of glass: (a) flows into the automotive stock; (b) stock of glass in the automotive sector; (c) flows into buildings; (d) stock of glass in buildings. The circles represent measured flow data which is provided in Supporting Information S2

A significant portion of container glass is currently recycled, displacing demand for virgin materials and reducing energy intensity and CO<sub>2</sub> emissions. Yet, glass recycling rates remain highly dependent on geographic location, reaching as high as 70% in Europe (Butler & Hooper, 2019) with considerable potential to improve in other countries. Increasing the amount of recycled glass also improves the melting yield, due to the overall reduction in process emissions.

There is uncertainty in the flows represented in Figure 1. No data was found on the production of glass fibers used in reinforced polymer composites, however, demand in this sector is likely to be growing. Extending the global map to include glass fibers and other products, would increase mass of material mapped by 5–10%. Harder (2018) reports that flat and container glass represent 94% of global glass production but Glass Alliance (2019) reports that approximately 8% of glass production in the European Union is neither flat nor container glass.

Uncertainty is also present in the four parameters used to construct the diagram. Table 3 shows how the major flows of the diagram would vary, with 1% increase for each of these parameters. For example, increasing the batch-to-melt yield would reduce the demand for virgin materials by up to 8%. Changing the yield of fabrication ( $\gamma$ ) impacts the internal recycling loop of the glass making processes, influencing the energy intensity and emissions of glass making. Furthermore, the recycling rate ( $\epsilon$ ) varies significantly by geographical region but has little influence on whether glass is recycled or landfilled. Uncertainty exists for the sector split, especially for container glass where no global data was found, however changes in the sector split have little effect on the rest of the diagram.

## 4.2 | Stock and flows of glass over time

Figure 3 shows that the stocks of glass in vehicles and buildings are projected to more than double between now and 2050. Figure 1 shows there is more glass produced for buildings than for vehicles, and the lifetime of buildings is 75 years, whereas vehicles only last 13 years on average. The differences in average lifetime affect the inflows and outflows in Figure 3a,c. High growth in stocks means that flat glass will have to be produced from virgin feedstock for the foreseeable future, as arising scrap is limited (container glass cullet is not used to produce flat glass because it does not meet the purity requirements (de Lumen & Schreuder, 2013)).



**TABLE 4** Material efficiency strategies and opportunities for glass (adapted for glass from Allwood et al. (2012))

Strategies	Opportunities within the glass supply chain	CO <sub>2</sub> saving estimates
Reducing yield losses	Material yield losses in glass manufacturing processes are relatively small, and lost glass material is routinely remelted. However, remelting waste glass increases the energy use and emissions for melting, so should be avoided where possible. This is more relevant for flat glass production, where the internal recycling loop is larger. Downstream fabrication processes result in further yield loss and waste glass requires careful cleaning and sorting to enable recycling in the melting furnaces.	Minimal savings
Diverting manufacturing scrap	Flat glass offcuts could be used for smaller products, however, in general, the glass lost during fabrication processes is difficult to recover with breakages, unlikely to be suitable for use in another application.	Minimal savings
Reusing components	Container glass could be reused more widely, reducing the need for remelting and fabrication. According to Butler and Hooper (2019), Europe reuses 4% of its container glass and Canada 68%. Demand for “virgin” containers could be reduced if other regions matched these reuse rates. In theory, the production of virgin containers could be limited to replacing damaged containers and meeting increases in demand.	If the whole world were to have the same reuse rate as Canada, 38% of emissions would be saved (40.3 Mt of CO <sub>2</sub> )
Using less material by design	Flat glass in buildings contributes to insulating the building fabric from cold and hot outside temperatures, hence there is a trade-off between use-phase and manufacturing energy demand. Limited reductions in the weight of glass containers might be achieved by increasing the repeatability of forming processes (thus requiring smaller margins of safety) and using the finite element method to accurately quantify the stresses applied to containers during use thus optimizing the use of material. vetropack (2012) were able to reduce the mass of their containers by approximately 10% through careful design.	If all the containers were 10% lighter by 2050, the emissions from glass making would be reduced by 6% (5.9 Mt of CO <sub>2</sub> )
Longer life products	Extending the lifetime of buildings and vehicles will result in reduced demand for replacement glass used in these products. However, this must be traded against the rapid technical development in glass products, such as windows, where thermal and optical properties are evolving rapidly.	Extending the lifetime of vehicles from 13 to 20 years would reduce CO <sub>2</sub> emissions by 2% in 2050 (1.8 Mt of CO <sub>2</sub> )
Reducing final demand	The more efficient use of buildings and vehicles could reduce overall demand for glass in these products. Moving from single use glass containers for beverages, to multiple use containers, and fountain beverage delivery systems, can help. For example, delivering beer from casks to reusable glass instead of single use glass bottles.	Saving unknown

Since most of the flat glass is produced without the use of cullet, there is potential to use the stock outflows and reduce the amount of landfilled material and glass production emissions. There are, however, challenges with recovering glass from vehicles and buildings with the current practice being to treat the glass as a waste product in metal recycling for cars. Flat glass is often laminated, where each glass sheet is made of multiple layers of glass bonded by a polymer interlayer. Removal of this interlayer requires an additional processing step to recycle the material, increasing recovery costs and limiting process yields. Besides the polymer interlayer, other impurities such as coatings, sealants, or other adhesives compromise the feasibility of recycling.

The main source of uncertainty within the dynamic analysis is the use of steel in buildings as a proxy for glass demand. It is likely that the average lifetime of flat glass in buildings is lower than 75 years. The glass stock in buildings is therefore overestimated and the outflows are underestimated. Less uncertainty is anticipated for the stock of glass in vehicles as these vary less in size and weight than buildings. Furthermore, the average mass of glass in cars is sourced directly from bottom-up data, from Dai et al. (2016), rather than being estimated indirectly.

### 4.3 | Material efficiency options

Allwood et al. (2012) defined six material efficiency strategies, which are applied in Table 4 to identify resource efficiency opportunities in the global supply chain for glass. As mentioned in Section 1, there have been studies that aimed to reduce CO<sub>2</sub> emissions in glass making by improving energy efficiency (e.g., Scalet et al. (2013), Schmitz et al. (2010) and Springer and Hasanbeigi (2017)). There are less attempts of achieving a similar goal by taking advantage of material efficiency. This subsection uses the material efficiency strategies proposed by Allwood et al. (2012) as inspiration to search and quantify CO<sub>2</sub> emission reduction opportunities. This analysis is only possible due to the static and dynamic material flow models developed in this study.



In Section 1, the global emissions from glass making were estimated at 86 Mt of CO<sub>2</sub>. If the predictions of Figure 3 are accurate, and the emission intensity of glass making remains constant, by 2050, this industry will generate<sup>2</sup> 107 Mt of CO<sub>2</sub> (an increase of 25% over 2014). Table 3 provides a list of actions that could reduce this figure, reusing containers at a large scale could enable a CO<sub>2</sub> emissions reduction of 38%.

The use of recycled cullet should be promoted over virgin glass production, as this reduces the energy use and emissions from melting by up to 40%. However, the reuse of glass products, without any melting at all, results in emissions savings close to 100%. The reuse of flat glass is close to non-existent, due the increased quality requirements of new buildings, differences in window sizes, and technical difficulty and costs removing intact window glass from buildings. The lifetime of flat glass in buildings can easily be extended by using the building for longer. However, light-weighting flat glass by fabricating thinner sections is not considered feasible, as flat glass is already close to the minimum thickness limit.

Perhaps the most important determinant of the amount of glass used in buildings is the type of glazing unit. A double-glazed unit requires about two times as much glass as a single-glazed unit. However, double-glazing reduces heat and cooling loads over single glazing which saves energy and emissions. Double-glazed units provide significant thermal benefits, which in most cases outweigh the additional carbon investment for extra glazing panes. However, the balance depends on the windows being kept in service for many years. The advancement of double-glazed units with low emissivity coatings reduces heat loss by 75% compared to single glazing, and by 40% compared to conventional double glazing. Higher building occupancy rates could reduce overall demand for flat glass, as would a reduction in the glazed fraction of building walls.

Reusing container glass acts equivalent to extending the lifetimes or increasing the intensity of use. Standardization of container glass sizes, designs, and colors could greatly improve the potential for reuse. Light weighting of container glass is an established practice, however, may be approaching practical minimum limits. Weight reduction is made possible due to new manufacturing techniques and by thoroughly analyzing the glass, for example, using the finite element method to calculate internal stresses.

## 4.4 | Conclusion

In this paper, we have mapped the flow of container and flat glass from raw materials to end of life, for the year 2014. A dynamic model of glass products for the glass industry reveals the importance of glass in buildings, where large inflows and long lifetimes mean considerable glass is tied up in stocks. The diversity of glass products means that different material efficiency strategies are likely to deliver varying savings across the breath of products.

In future work, we would like to model emission intensities for each process step to provide a detailed model of emissions from the glass industry. Furthermore, a cost-benefit analysis would help decide which material efficiency strategies are most effective. Finally, research is required into social, economic, and technical barriers that prevent the implementation of material efficiency strategies.

## CONFLICT OF INTEREST

The authors declare no conflict of interest.

## ORCID

Matteo Craglia  <https://orcid.org/0000-0001-6363-5423>

José M. C. Azevedo  <https://orcid.org/0000-0003-3294-2775>

Jonathan M. Cullen  <https://orcid.org/0000-0003-4347-5025>

## REFERENCES

- Allwood, J. M., Cullen, J. M., Carruth, M. A., Cooper, D. R., McBrien, M., Milford, R. L., ... & Patel, A. C. H. (2012). *Sustainable materials: With both eyes open*. UIT Cambridge Limited.
- Azevedo, J. M. C. (2020). Code supporting "Global Material Flow Analysis of Glass: From Raw Materials to End-of-Life". Zenodo. <https://doi.org/10.5281/zenodo.4304618>.
- Butler, J. H., & Hooper, P. D. (2011). Glass waste. In T. Letcher & D. Vallero (Eds.), *Waste* (pp. 151–165). Academic Press.
- Butler, J. H., & Hooper, P. D. (2019). Glass waste. In T. Letcher & D. Vallero (Eds.), *Waste* (pp. 307–322). Academic Press.
- Brinckerhoff, W. P. (2015). *Industrial decarbonisation and energy efficiency roadmaps to 2050: Glass*. WSP Parsons Brinckerhoff.
- British Glass. (2008). UK glass manufacture: A mass balance study. *British Glass, Sheffield*.
- Cao, Z., Shen, L., Løvik, A. N., Müller, D. B., & Liu, G. (2017). Environmental Science & Technology, 51(19), 11468–11475.
- Cooper, D. R., Skelton, A. C., Moynihan, M. C., & Allwood, J. M. (2014). Component level strategies for exploiting the lifespan of steel in products. *Resources, Conservation and Recycling*, 84, 24–34.
- Cullen, J. M. (2017). Circular economy: Theoretical benchmark or perpetual motion machine? *Journal of Industrial Ecology*, 21(3), 483–488.
- Cullen, J. M., Allwood, J. M., & Bambach, M. D. (2012). Mapping the global flow of steel: From steelmaking to end-use goods. *Environmental Science & Technology*, 46(24), 13048–13055.

<sup>2</sup> Assuming that production of "Other flat glass" and container glass increased at the same rate as the population projections used in the dynamic analysis of glass in vehicles.

- Cullen, J., & Allwood, J. (2013). Mapping the global flow of aluminum: From liquid aluminum to end-use goods. *Environmental Science & Technology*, 47(7), 3057–64.
- Dai, Q., Kelly, J., & Elgowainy, A. (2016). Vehicle materials: Material composition of US light-duty vehicles. *Energy Systems Division, Argonne National Labs: Chicago, USA*, pp. 1–30.
- de Lummen, G. V. M., & Schreuder, N. (2013). Views from the flat glass industry: AGC Glass Europe. <https://agc-flattoflat.eu/wp-content/uploads/2017/01/Recycling-of-Glass-from.pdf>
- European Commission. (2008). FWC sector competitiveness studies - Competitiveness of the glass sector. <https://ec.europa.eu/docsroom/documents/1989/attachments/1/translations/en/renditions/native>
- European Commission. (2012). Internal market, industry, entrepreneurship and SMEs: Glass. [https://ec.europa.eu/growth/sectors/raw-materials/industries/non-metals/glass\\_en](https://ec.europa.eu/growth/sectors/raw-materials/industries/non-metals/glass_en)
- Glass Alliance. (2019). European glass industries: statistical report 2018–2019. <https://www.wko.at/branchen/industrie/glasindustrie/statistical-report-glass-alliance-europe-2018-2019.pdf>
- Glass for Europe. (2018). World market structure. <http://www.glassforeurope.com/en/industry/global-market-structure.php>
- Glass Packaging Institute. (2014). Shipment Reports 2014. <http://www.gpi.org/industry-resources/shipment-reports>
- Harder, J. (2018). Glass recycling – Current market trends. [https://www.recovery-worldwide.com/en/artikel/glass-recycling-current-market-trends\\_3248774.html](https://www.recovery-worldwide.com/en/artikel/glass-recycling-current-market-trends_3248774.html)
- IEA. (2007). *Tracking industrial energy efficiency and CO<sub>2</sub> emissions*. OECD Publishing, Paris. <https://doi.org/10.1787/9789264030404-en>
- IEA. (2020). Global CO<sub>2</sub> emissions in 2019. <https://www.iea.org/articles/global-co2-emissions-in-2019>
- Laner, D., Rechberger, H., & Astrup, T. (2014). Systematic evaluation of uncertainty in material flow analysis. *Journal of Industrial Ecology*, 18(6), 859–870.
- Levi, P. G., & Cullen, J. M. (2018). Mapping global flows of chemicals: From fossil fuel feedstocks to chemical products. *Environmental Science & Technology*, 52, 1725–1734.
- Levine, E., Greenman, M., & Jamison, K. (2003). The development of a next generation melting system for glass production: Opportunities and progress. *Proceedings from the ACEEE Summer Studies on Energy Efficiency in Industry*, [https://www.eceee.org/library/conference\\_proceedings/ACEEE\\_industry/2003/Panel\\_4/p4\\_16/](https://www.eceee.org/library/conference_proceedings/ACEEE_industry/2003/Panel_4/p4_16/).
- Lucintel. (2016). Growth opportunities in the global flat lass market trends, opportunities and forecast in this market to 2021 by application (building construction glass, automotive glass, speciality glass), and region (North America, Europe, Asia Pacific and Rest of the World). <https://www.lucintel.com/flat-glass-market,-flat-glass-industry.aspx>
- Lupton, R. C., & Allwood, J. M. (2017). Hybrid Sankey diagrams: Visual analysis of multidimensional data for understanding resource use. *Resources, Conservation and Recycling*, 124, 141–151.
- Modaresi, R., Pauliuk, S., Løvik, A. N., & Müller, D. B. (2014). Global carbon benefits of material substitution in passenger cars until 2050 and the impact on the steel and aluminum industries. *Environmental Science & Technology*, 48(18), 10776–10784.
- Müller, D. B. (2006). Stock dynamics for forecasting material flows—Case study for housing in The Netherlands. *Ecological Economics*, 59(1), 142–156.
- Pauliuk, S., Milford, R. L., Müller, D. B., & Allwood, J. M. (2013a). The steel scrap age. *Environmental Science & Technology*, 47(7), 3448–3454.
- Pauliuk, S., Wang, T., & Müller, D. B. (2013b). Steel all over the world: Estimating in-use stocks of iron for 200 countries. *Resources, Conservation and Recycling*, 71, 22–30.
- Pauliuk, S., & Mutel, C. (2014). *dynamic\_stock\_model*. GitHub. [https://github.com/stefanpauliuk/dynamic\\_stock\\_model](https://github.com/stefanpauliuk/dynamic_stock_model)
- Pilkington. (2010). Pilkington and the flat glass industry. <https://www.pilkington.com/en-gb/uk/about/downloads/corporate-publications/pilkington-and-the-flat-glass-industry-2010>
- Robertson, G. L. (2005). *Food packaging: Principles and practice*. CRC press.
- Saint-Gobain. (2009). More-is-less” with unique cullet recycling scheme. <http://scandinavia.saint-gobain-glass.com/node/199>
- Sandgren, K. (1996). Material flow analysis for an industry—A case study in packaging. *Natural Resources Research*, 5, 235–247
- Scalet, B. M., Garcia Muñoz, M., Sissa, A. Q., Roudier, S., & Delgado Sancho, L. (2013). Best available techniques (BAT) reference document for the manufacture of glass. *Sevilla: Joint Research Centre of the European Commission (JRC)*.
- Schmitz, A., Kamiński, J., Maria Scalet, B., & Soria, A. (2010). Energy consumption and CO<sub>2</sub> emissions of the European glass industry. *Energy Policy*, 39, 142–155.
- Shelby, J. E. (2005). *Introduction to glass science and technology*. Royal Society of Chemistry.
- Springer, C., & Hasanbeigi, A. (2017). *Emerging energy efficiency and carbon dioxide emissions-reduction technologies for the glass industry*. [https://china.lbl.gov/sites/default/files/lbl\\_glass\\_final.pdf](https://china.lbl.gov/sites/default/files/lbl_glass_final.pdf)
- Tsai, C. L., & Krogmann, U. (2013). Material flows and energy analysis of glass containers discarded in New Jersey, USA: Material flows/energy analysis of glass containers. *Journal of Industrial Ecology*, 17(1), 129–142.
- United Nations. (2019). *Industrial commodity statistics yearbook: Production statistics (2007–2016). Volume, I*. United Nations Publications.
- Van Ewijk, S., Stegemann, J. A., & Ekins, P. (2018). Global life cycle paper flows, recycling metrics, and material efficiency. *Journal of Industrial Ecology*, 22(4), 686–693.
- vetropack. (2012). A lighter way to enjoy glass. [https://www.vetropack.at/fileadmin/doc/01\\_publications/04\\_Brochures/leichtglas\\_en.pdf](https://www.vetropack.at/fileadmin/doc/01_publications/04_Brochures/leichtglas_en.pdf)
- Wiedenhöfer, D., Fishman, T., Lauk, C., Haas, W., & Krausmann, F. (2019). Integrating material stock dynamics Into economy-wide material flow accounting: Concepts, modelling, and global application for 1900–2050. *Ecological Economics*, 156, 121–133. <https://doi.org/10.1016/j.ecolecon.2018.09.010>.
- Worrell, E., Galitsky, C., Masanet, E., & Graus, W. (2008). Energy efficiency improvement and cost saving opportunities for the glass industry. <https://www.energystar.gov/sites/default/files/buildings/tools/Glass-Guide.pdf>.

## SUPPORTING INFORMATION

Additional supporting information may be found online in the Supporting Information section at the end of the article.

**How to cite this article:** Westbroek CD, Bitting J, Craglia M, Azevedo JMC, Cullen JM. Global material flow analysis of glass: From raw materials to end of life. *J Ind Ecol*. 2021;25:333–343. <https://doi.org/10.1111/jiec.13112>